

UNITED STATES DEPARTMENT OF THE INTERIOR BUREAU OF MINES HELIUM ACTIVITY HELIUM RESEARCH CENTER

INTERNAL REPORT

CONCERNING PHYSICAL PARAMETERS

FOR USE IN AN ABSOLUTE GAS VISCOSIMETER

BY

R. A. Guereca
H. P. Richardson
J. L. Gordon
J. E. Miller

BRANCH

BRANCH OF FUNDAMENTAL RESEARCH

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R. A. Guereca, $\frac{1}{H}$. P. Richardson, $\frac{2}{I}$ J. L. Gordon, $\frac{2}{I}$ and J. E. Miller $\frac{2}{I}$

ABSTRACT

Accurate measurements of physical dimensions of a section of stainless steel capillary tubing are presented and used to develop a final working equation for an absolute gas viscosimeter. The effects of pressure and temperature on these dimensions are considered. The internal surface finish and non-uniformity of the capillary bore are discussed as well as entrance, kinetic energy, gas slippage, and gas compressibility correction factors.

INTRODUCTION

The Bureau of Mines Helium Research Center is using a 208-foot long, thick-walled, stainless steel capillary tube, 0.030 inch in internal diameter, wound in the form of a helix 20 inches in diameter,

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R. A. Guereca, M. P. Richerdson, J. L. Cordon, J. and J. E. Miller &

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Accurate consorraments of physical disensions of a section of stainless seed contillary tubing see presented and used to develop a final working equation for an absolute gas viacosizeter. The effects of presence and temperature on these dimensions are considered. The laternal surface finish and non-uniformity of the capillary bure are discussed as well as entrance, kinetic energy, gas slippage, and gas evapressibility correction factors.

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to determine viscosities for pure gases and mixtures at high pressure levels. A coiled capillary of the above dimensions is necessary at high pressures in order to obtain accurately measurable pressure drops at very low volumetric flowrates and to maintain a uniform temperature over the entire length; further, certain correction factors are minimized. Absolute viscosities, reproducible to an accuracy of one micropoise or better, are being evaluated. The values are absolute, insofar as calibration with a gas of known viscosity is not required. Prior to this, a 32-foot long capillary of the same dimensions was used for the experimental determination of steady-state laminar flow boundary conditions applicable to the coiled system.

Accurate measurements of the physical dimensions of a capillary section were made by the Atomic Energy Commission Pantex Plant, Amarillo, Texas. All measurements were taken under controlled environmental conditions.

The intent of this report is to present these measurements, show how they are used in determining certain physical parameters of interest, and develop a viscosity equation which includes corrections for the effects of the temperature and pressure levels on these parameters. The parameters are: mean radius, $R_{\rm m}$, of the capillary tubing; variation of individual radii, $R_{\rm i}$, with length, $L_{\rm i}$; and total length, $L_{\rm T}$.

The correction for non-uniformity of the capillary bore or variations in R along L is shown to be negligible through the use of a correction factor, δ . In a later section, the entrance or Couette cor-

to determine viscosities for pure pases and mixtures at high pressure.

Invels. A colled capillary or the above dimensions is necessary at high pressures in order to obtain accurately measurable pressure drops at very low volumetric floweness and to maintain a uniture temperature over the entire length; forther, nertain correction factors are minimized. Absolute viscosities, reproducible to an accuracy of one mixturopoies or better, are being evaluated. The values are absolute, insofar as calibration with a was of known viscosity is not required.

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tions in A sloom is to shown to be negligible through the use of a correction factor, A. In a later scation, the entrance of Couetro cor-

rection, involving R_m and L_T , is shown to be negligible; the kinetic energy correction, involving R_m^4 when expressed in pressure units, and gas slippage at the walls of the capillary, involving R_m and the mean free path of the molecules, λ , also are shown to be negligible at the pressure and temperature levels of interest. The effect of gas compressibility, which does not involve a direct metrological determination, is discussed and shown to be negligible because of the very low pressure drops in the system.

At a given temperature (T) and pressure (P), the modified Poiseuille equation, incorporating the physical parameters just mentioned, is:

$$\eta = \left[\frac{\pi R_{m}^{4} \triangle P_{e}}{8L_{T} \delta Q_{m}} \right],$$
(1)

where

 η = computed viscosity at (T,P), poises;

R_m = mean radius of the capillary tube if the bore
were uniform throughout, cm;

 $\triangle P_e$ = effective pressure drop used to overcome viscous resistance; measured pressure drop ($\triangle P_{me}$) corrected for kinetic energy effects, dynes/cm²;

 $L_{\rm T}$ = total length of capillary, cm;

δ = correction of actual capillary bore from a uniform, right circular cylinder, dimensionless;

 $Q_{\rm m}$ = mean volumetric gas flow rate, cm³/sec, at the mean system pressure, $P_{\rm m}$.

recation, invaliding R_m and h_p, is shown to be acquisibled the mines, and energy correction; involving t^A_m when suppressed to pressure units, and gas slipping at the walls of the capitlary, involving R_m and the seasoners perhod at the columnist, h, also are shown to see school to satisfying the compressibility, which does not involve a direct actual detaining.

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System presented for rece, or less, or the near

A vertical volumetric rate pump circulates gas isothermally through the capillary at a constant mean rate, $\mathbf{Q}_{\mathrm{m}};$ the pressure drop is measured by a precision-delta-pressure transducer. It is tacitly assumed that any basic errors in \mathbf{Q}_{m} and $\Delta\mathbf{P}_{\mathrm{me}}$ are negligible. Once the physical parameters $\mathbf{R}_{\mathrm{m}},$ $\mathbf{L}_{\mathrm{T}},$ and δ are known, as well as the effects of temperature and pressure on \mathbf{R}_{m} and $\mathbf{L}_{\mathrm{T}},$ the determination of viscosity basically involves plotting a series of values of $\Delta\mathbf{P}_{\mathrm{e}}$ versus \mathbf{Q}_{m} on rectangular coordinates and determining the slope of this straight line.

The necessity for highly accurate and precise physical measurements can be noted from equation (1) where $R_{\rm m}$ is raised to the fourth power. Assuming all other terms to be correct, if $R_{\rm m}$ is known to within 5 x 10⁻⁶ inch, the computed viscosity will be within 0.25 micropoise when the true value is of the order of 200 micropoises.

MEASUREMENT PROGRAM

The original measurement program was designed to cross-check R_m by two methods. The "metrometric" method consisted of measurements of out-of-roundness, internal diameters (ID), and internal roughness of 4-inch sections of the capillary. The "volumetric" method included measurements of the length, external diameters (OD), and weights of 12-inch sections. If the density is accurately known and is uniform, the volumetric method can be used to compute the ID of the capillary bore. All measurements were made at 293° K and 0 psig.

Measurements were taken on a 19-foot section selected at random from 1,000 feet of 347 stainless steel tubing supplied by Superior Tube

A vertical volumetric rate pune circulates yes isothermally through the capillary at a constant mean rate, 0, the presents drop is measured by a precision-delica-processe transducer. It is taulily assumed that any basic errors in 0, and of, are negligible. Once the physical parameters 2, 1, and there have as well as the effects of temperature and presents on 5, and 1, the determination of viscosity temperature and presents on 5, and 1, the determination of viscosity temperature planting a series of veloce of this straight time reconstitution of the straight time

The necessary for highly accurate and precise physical mescularization of the name of term aquation (1) where is a raised to the fourth power.

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MEASUREMENT THOUSAND

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Measurements were taken on a 19-foot section selected at random from 1,000 feet of 347 stainless steel tubing supplied by Superior 'Nube

Company. 3/ This "precision drawn instrument tubing" is nominally 0.122-

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inch OD and 0.030-inch ID. Average mechanical properties are: 149,500-psig ultimate tensile strength and 136,400-psig yield strength.

The 19-foot section was cut into 1-foot lengths for the volumetric program. Each segment was formed into a circular arc with a 10.00000-inch radius of curvature, using a special fixture (figure 1) because

Figure 1.-Fixture for length of bore measurements.

the viscosimeter tubing is wound into a 20-inch diameter helix. The length and four OD's were measured for each section. The 1-foot lengths were weighed on an analytical balance before being cut into three 4-inch lengths. At each end of the 4-inch samples, three ID's, 60 degrees apart, were measured at a depth of 1/16 inch, and a profile of the out-of-roundness was taken at the same depth. The 4-inch samples were held in another fixture (figure 2) constructed to have the same 10.00000-inch

Figure 2.-Fixture for ID measurements and out-of-roundness profiles.

radius of curvature. By the above procedure, a total of 114 out-of-

Company. This "precision drawn instrument many" is newfrally 0.422-

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program. Each reguent was formed into a circular are with a landsom-

Figure 1 -Fixture for length of hore mental months.

the visconfractor thems is wrond into a 70-inch diameter heles. The length and lang on an analysical belace before being mut rate three solution tengths, were measured for each sentian. The location three solution tengths, at each and of the definition and a profite of the cut-appear, were measured at a depth of life inche and a profite of the cut-of-roundance was then at the one depth. The desirch samples were used to another fixture (figure 2) apprendent to have the same 10.00000-in.)

Figure & - Statemen for the measurements and our - of constitute profities.

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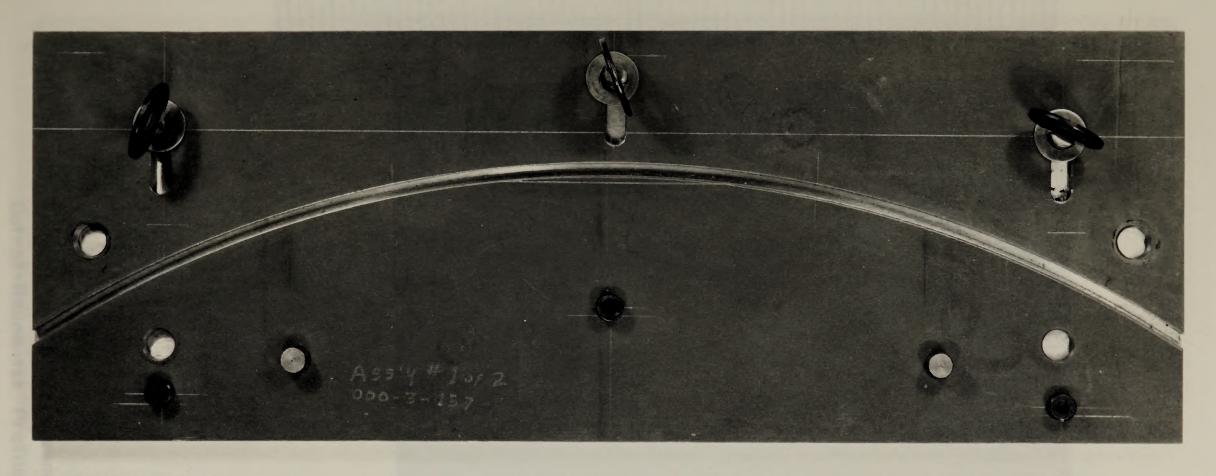
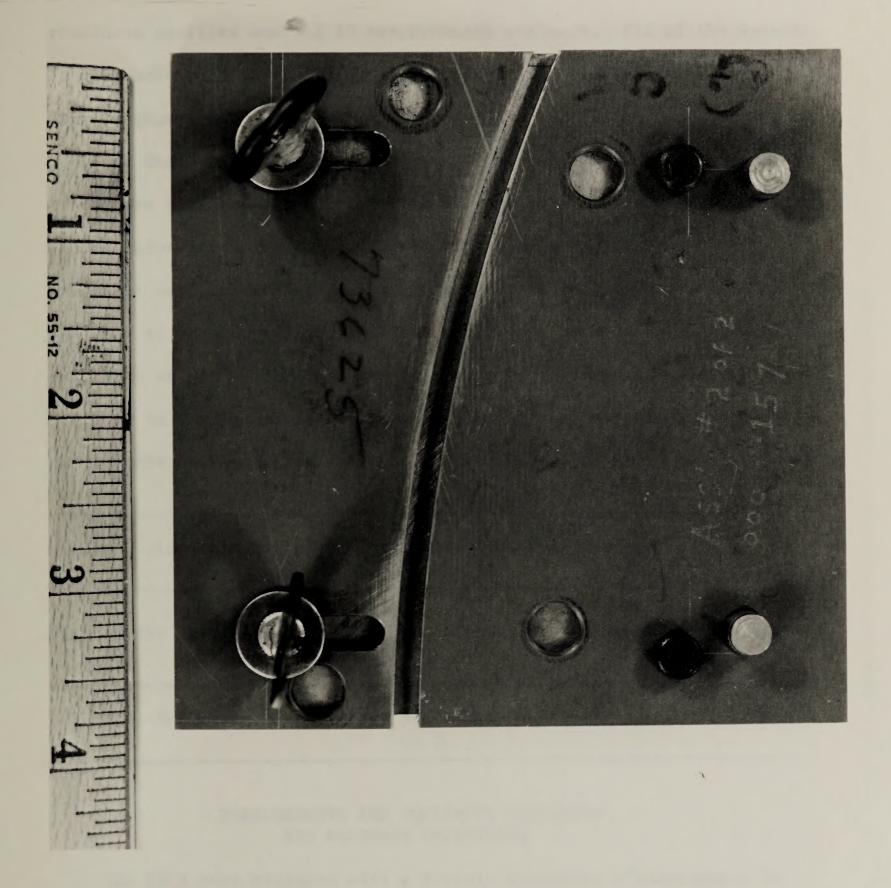
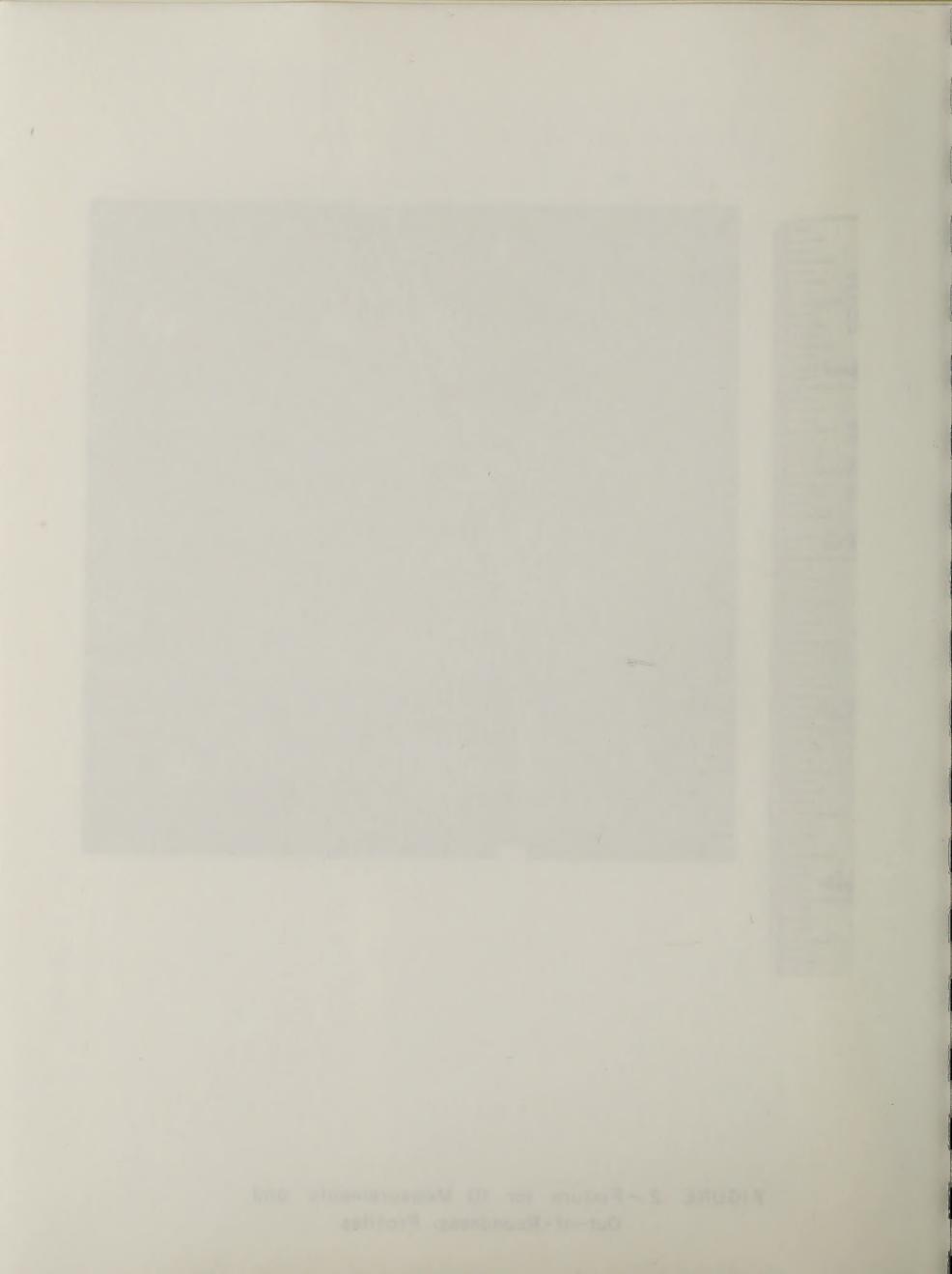




FIGURE 1.—Fixture for Length of Bore Measurements







roundness profiles and 342 ID measurements was made. Six of the 4-inch lengths were randomly selected for longitudinal internal finish or surface roughness measurements.

The desired lengths were cut with a saw and the ends ground smooth and square with a surface grinder to minimize distortion and provide a smooth reference surface. The surface grinder also was used to expose the inner surface for internal roughness determinations. A microscope was used to examine exposed internal surfaces. No evidence of distortion was found at the measurement depth. The out-of-roundness apparatus also was used to examine cross section profiles at various depths and showed no evidence of distortion due to cutting. Figure 3 shows a longitudinal

Figure 3.-Longitudinal view of capillary internal surface.

view of the internal surface; figure 4 shows end views of the capillaries.

Figure 4.-End view of capillary bores.

MEASUREMENTS AND EQUIPMENT PRECISION AND ACCURACY CAPABILITY

The ID's were measured with a Societe Genevoise D'Instruments De Physique Universal Measuring Machine, Model MU-214B, called the "SIP." A special gaging stylus, 0.005 inch in radius, was fabricated and used in conjunction with the holding fixture which vertically supported the capillary sections. Individual diameters measured with this instrument

roundance profiles and 342 to mensurements was made. Six of the 4-inch tengths were randomly amicored for longitudinal internat finish or sur-

The desired lemaths supply cut with a saw and the ends prount amount and aquare with a surface at the surface attached also was used to expose the inner surface toy internal roughness determinations. A interscope was used to examine expand internal surfaces. The put-of-community approximation and examine was reasoned at the measurement depth. The put-of-community apparatus also was used to examine cross sweeten profiles at various depths and showed no evidence of distortion due to courts. Finds I some a longitudinal

Figure 3.-Longitudinal view of copiliary internal suctions.

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Figure 4 . - End when of capillary borns

AND ACCORACT CAPABILITY

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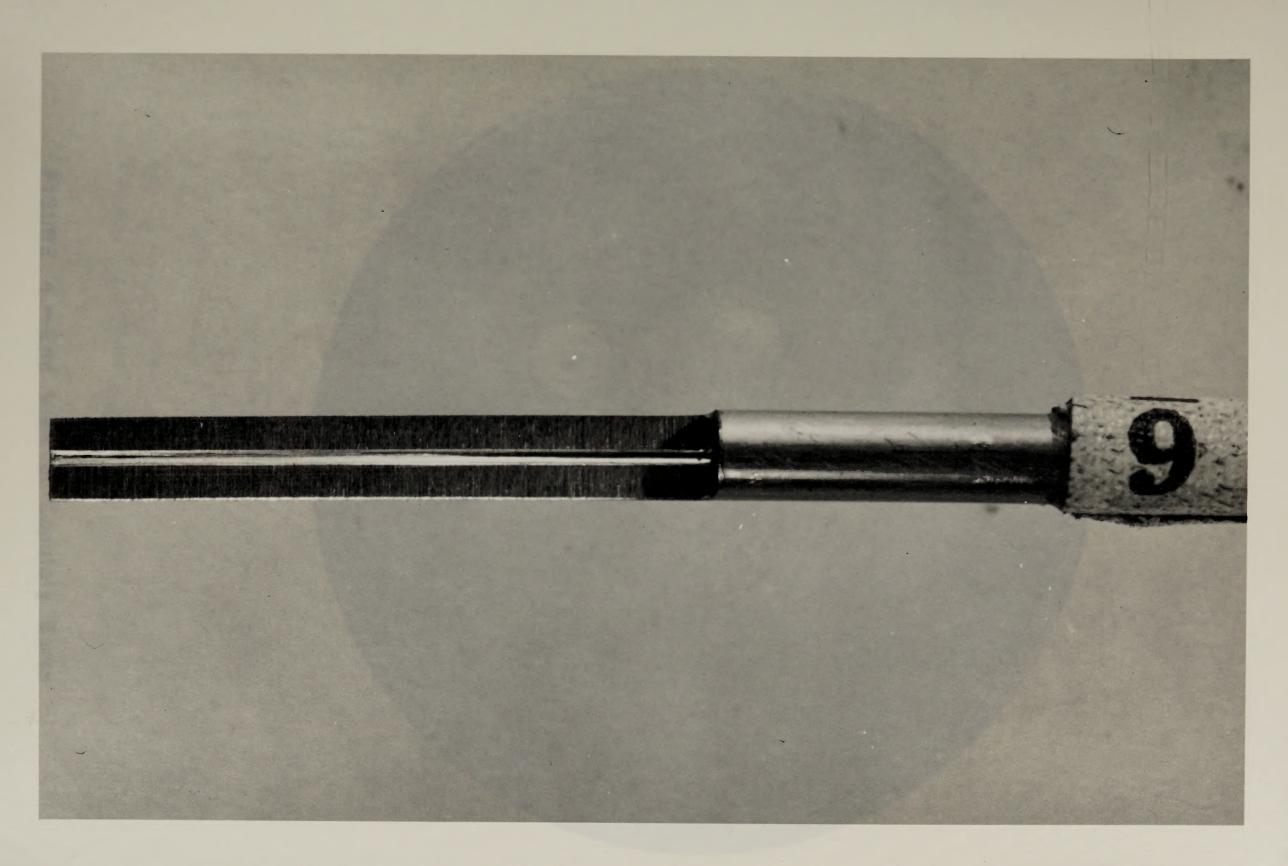


FIGURE 3.- Longitudinal View of Capillary Internal Surface



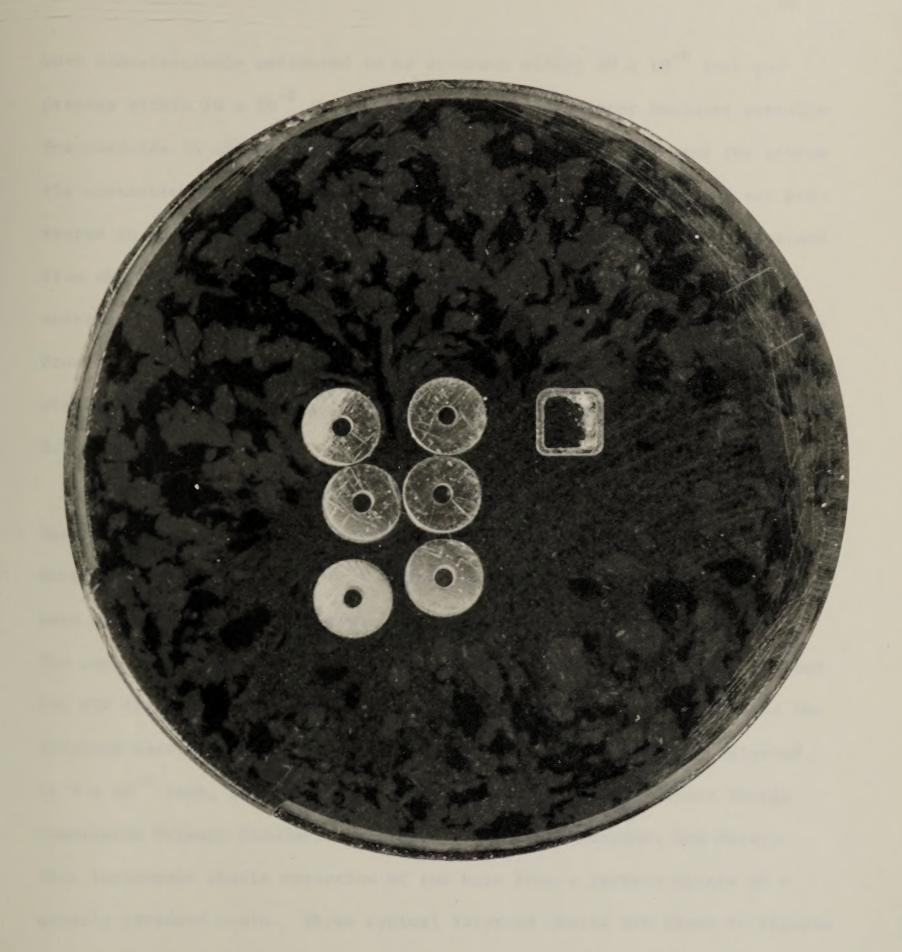


FIGURE 4.— End View of Capillary Bores



were conservatively estimated to be accurate within 20×10^{-6} inch and precise within 10×10^{-6} inch. The error of measurement includes possible inaccuracies in stylus deflection, internal surface finish, and the stylus tip contacting the inner surface. Results of the ID measurements are presented in table 1 and include the average radius for each section obtained from the 0° , 60° , and 120° SIP measurements; each 4-inch length had a reference mark on both ends to represent the 0° angle. The average radius from all SIP measurements is 0.015199 inch and is considered to be accurate to within 10 microinches, corresponding to a computed viscosity within 0.5 micropoise.

Cross section or out-of-roundness profiles were taken with an Engis Equipment Company "Talyrond" Machine manufactured by Taylor, Taylor, and Hobson (Leicester, England). A special gaging stylus of approximately the same dimensions as the SIP stylus was used in the Talyrond instrument. The capillary tubes were held on the Talyrond in the same fixture utilized for SIP internal diameter measurements. The reference mark identified the Talyrond charts with the SIP measurements. The accuracy of the Talyrond is 3 x 10^{-6} inch, according to standards certified by the Atomic Energy Commission Primary Standards Laboratory (ALO), Albuquerque, New Mexico. This instrument charts deviation of the bore from a perfect circle on a greatly expanded scale. Three typical Talyrond charts are shown in figures 5, 6, and 7 and show, respectively, circular, trilobular, and irregular

Figure 5.-Cross section profile of a circular capillary bore.

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were communicatively engineered to be accounted within 20 x 10 " inch and precise within 10 x 10 " inch. The error of measurement incides possible inscring in signic defication, increase sarface finish, and the orginal tip controling the former surface. Neguine of the limit are pre-

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Figure 5.-Cross section profile of a circular aspillary bore.

TABLE 1. - <u>Internal diameter measurements</u>

Sample number		Internal dia	umeter,	Average radius, inch
	0°	60°	120°	
1-1-A	0.03046	0.03045	0.03048	0.015232
1-1-B	.03057	.03049	.03041	.015245
2-1-A	.03039	.03035	.03044	.015197
2-1-B	.03051	. 03041	.03031	.015205
3-1-A	.03039	.03040	.03041	.015200
3-1-B	.03045	.03046	.03043	.015223
				.015217
1-2-A	0.03041	0.03043	0.03048	0.015220
1-2-B	.03030	. 03044	.03046	.015200
2-2-A	.03046	.03050	.03048	.015240
2-2-B	.03050	. 03045	.03056	.015252
3-2-A	.03048	.03051	.03054	.015255
3-2-B	.03055	.03051	.03046	015253
				.015237
1-3-A	0.03033	0.03035	0.03044	0.015187
1-3-В	.03058	.03052	.03046	.015260
2-3-A	.03047	.03043	.03054	.015240
2-3-B	.03044	.03049	.03042	.015225
3-3 - A	.03043	٥3039	.03030	.015187
3-3-B	.03043	.03031	.03035	.015182
				.015214
1-4-A	0.03031	0.03029	0.03030	0.015150
1-4-B	.03039	.03035	.03038	.015187
2-4-A	.03045	.03039	.03038	.015203
2-4-B	.03041	.03037	.03038	.015193
3-4-A	.03032	.03040	.03031	.015172
3-4-B	.03041	.03045	.03043	.015215
				.015187
1-5-A	0.03031	0.03036	0.03032	0.015165
1-5-B	.03040	。03039	.03038	.015195
2-5-A	.03045	.03039	.03041	.015208
2-5-B	.03038	.03041	.03036	.015192
3-5-A	.03045	.03046	.03039	.015217
3-5-B	.03043	.03035	.03038	015193
				.015195

TABLE I - Internal dissels; severe - I Miller

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		12,000	
.015218			

TABLE 1. - <u>Internal diameter measurements</u> - Continued

Sample number	I	nternal diamet	ter,	Average <u>radius, inch</u>
	0°	60°	120°	
1-6-A	0.03036	0.03041	0.03043	0.015200
1-6-В	.03031	.03032	.03034	.015162
2-6-A	.03042	.03040	.03045	.015212
2-6-B	.03045	.03043	.03043	.015218
3-6-A	.03043	.03041	.03040	.015207
3-6-B	.03037	.03034	.03036	015178
				.015196
1-7-A	0.03036	0.03033	0.03031	0.015167
1-7-B	.03041	。03032	.03036	.015182
2-7-A	.03042	.03036	.03039	.015195
2-7-B	.03038	.03037	.03041	.015193
3-7-A	.03042	.03046	.03037	.015208
3-7-B	.03040	.03043	.03042	.015208
				.015192
1-8-A	0.03038	0.03042	0.03042	0.015203
1-8-B	.03043	.03037	.03038	.015197
2-8-A	.03038	.03039	.30336	.015188
2-8-B	، 03045	.03047	.03046	.015230
3-8-A	.03046	.03048	.03045	.015232
3-8-B	.03047	.03044	.03041	.015220
				.015212
1-9-A	0.03050	0.03041	0.03038	0.015215
1-9-B	.03039	.03036	.03042	.015195
2-9-A	.03047	.03041	.03045	.015222
2-9-В	.03043	، 03046	.03037	.015210
3-9-A	.03044	.03037	.03035	.015193
3-9-B	.03040	.03045	.03044	.015215
				.015208
1-10-A	0.03046	0.03043	0.03040	0.015215
1-10-B	.03045	.03040	.03042	.015212
2-10-A	.03037	.03038	.03035	.015183
2-10-В	.03043	.03044	.03042	.015215
3-10-A	.03040	.03037	.03041	.015197
3-10-В	.03044	.03040	.03041	015208
				.015205

TABLE L. - Ingernal diameter measurements - Continued

	,200	
		2-8-8

TABLE 1. - <u>Internal diameter measurements</u> - Continued

Sample number	I I I I I I I I I I I I I I I I I I I	nternal diame	ter,	Average radius, inch
	0°	60°	120°	
1-11-A	0.03040	0.03036	0.03038	0.015190
1-11-В	.03039	.03041	.03037	.015195
2-11-A	.03039	.03034	.03036	.015182
2-11-B	.03038	.03041	.03037	.015193
3-11-A	.03040	.03041	.03038	.015198
3-11-В	.03041	.03039	.03041	.015202
				.015193
1-12-A	0.03036	0.03036	0.03035	0.015178
1-12-B	. 03034	.03038	.03037	.015182
2-12-A	.03036	.03034	.03033	.015172
2-12-B	.03026	.03022	.03020	.015113
3-12-A	.03038	.03035	.03033	.015177
3-12-B	. 03035	03033 ،	.03032	015167
				.015165
1-13-A	0.03031	0.03034	0.03032	0.015162
1-13-B	.03035	.03040	。03035	.015183
2-13-A	. 03038	.03034	。03040	.015187
2-13-B	.03040	.03043	.03042	.015208
3-13-A	، 03036	.03042	.03037	.015192
3-13-B	.03042	.03040	.03042	015207
				.015190
1-14-A	0.03038	0.03041	0.03039	0.015197
1-14-B	.03039	.03043	.03042	.015207
2-14-A	.03044	.03043	.03045	.015220
2-14-B	. 03045	.03043	.03046	.015223
3-14-A	، 03045	.03044	.03042	.015218
3-14-B	.03044	。03046	.03043	.015222
				.015214
1-15-A	0.03045	0.03048	0.03046	0.015232
1-15-B	.03041	.03044	.03047	.015220
2-15-A	.03042	.03042	.03045	.015215
2-15-B	.03040	.03040	.03041	.015202
3-15-A	.03040	. 03044	. 03044	.015213
3-15-B	.03045	.03045	.03042	.015220
				.015217

TABLE 1. - Interpol discourt occurrence - Continued

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TABLE 1. - <u>Internal diameter measurements</u> - Continued

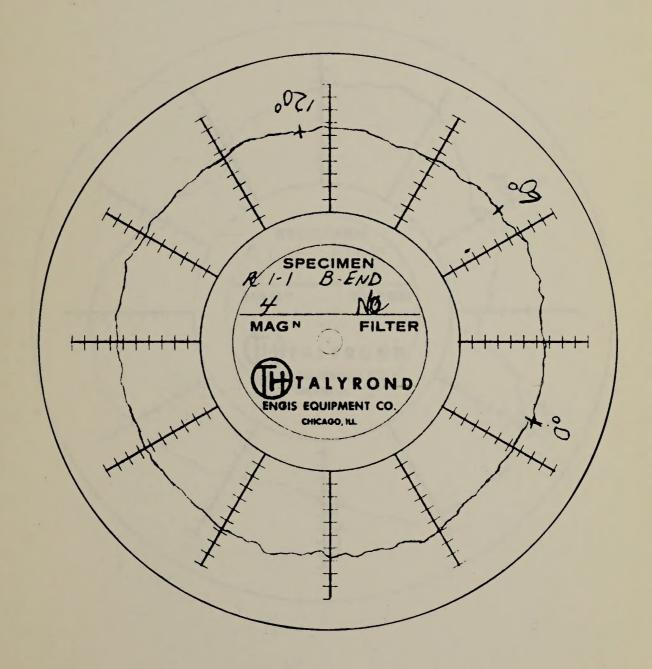
Sample number	Intern		,	Average radius, inch
	0°	60°	120°	
1-16-A	0.03041	0.03044	0.03045	0.015217
1-16-B	.03045	.03042	.03040	.015212
2-16-A	.03046	. 03047	.03045	.015230
2-16-B	.03046	. 03043	.03043	.015220
3-16-A	.03043	.03041	.03042	.015210
3-16-B	.03040	.03037	.03040	.015195
				.015214
1-17-A	0.03040	0.03039	0.03042	0.015202
1-17-B	.03043	.03042	.03040	.015208
2-17-A	.03045	.03044	.03046	.015225
2-17-B	.03041	.03039	.03040	.015200
3-17-A	.03034	.03038	.03033	.015175
3-17-В	.03032	.03035	。03035	.015170
				.015197
1-18-A	0.03037	0.03034	0.03033	0.015173
1-18-B	.03039	.03037	.03037	.015188
2-18-A	.03033	.03037	。03038	.015180
2-18-B	.03037	.03035	. 03024	.015160
3-18-A	.03033	.03030	.03028	.015152
3-18-В	.03034	.03031	.03031	015160
				.015169
1-19-A	0.03041	0.03036	0.03038	0.015192
1-19-В	.03033	.03024	.03026	.015138
2-19-A	.03034	.03032	.03023	.015148
2-19-B	.03027	。03030	.03034	.015152
3-19-A	.03030	.03029	。03034	.015155
3-19-B	.03031	.03032	。03032	015158
				015157

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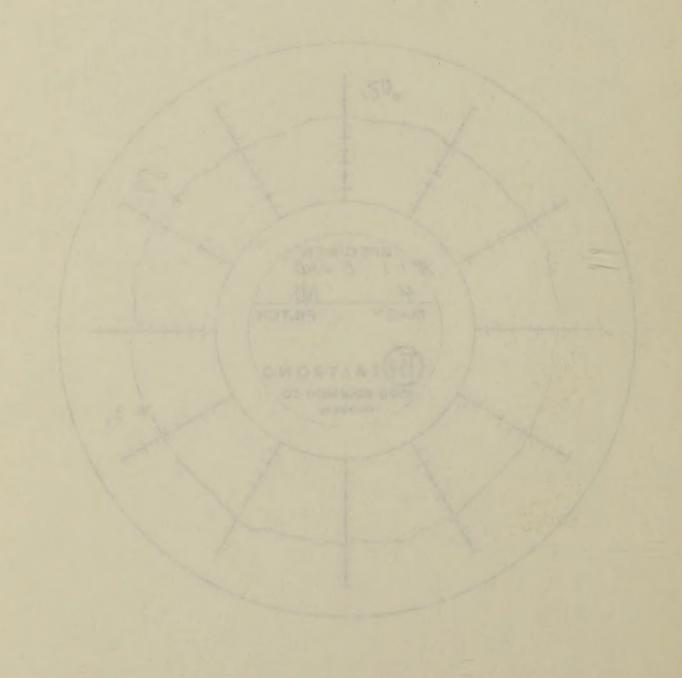
		nch	
Sample number		60°	120°
I-I-B	0.03057	0.03049	0.03041

Talyrond



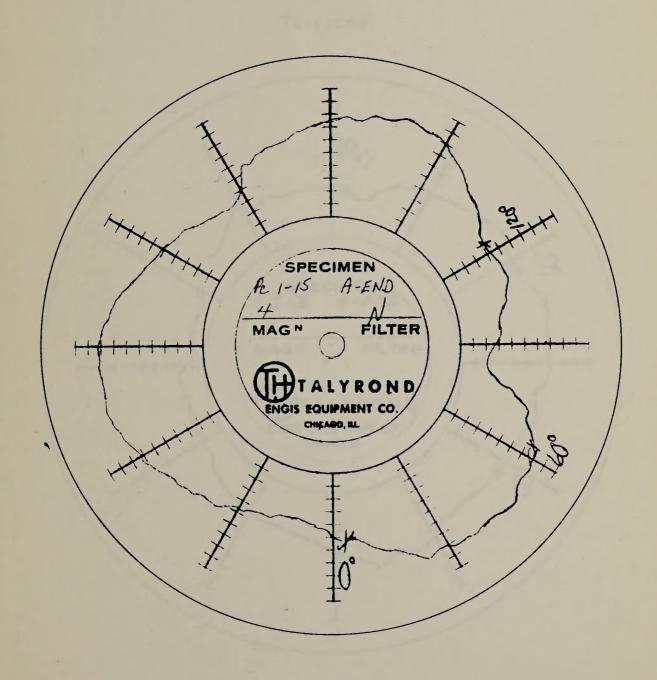
TOTAL PROPERTY STORES STORES STORES

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		Internal diameter, in	ich
Sample number	0°	60°	120°
1-15-A	0.03045	0.03048	0.03046

Talyrond

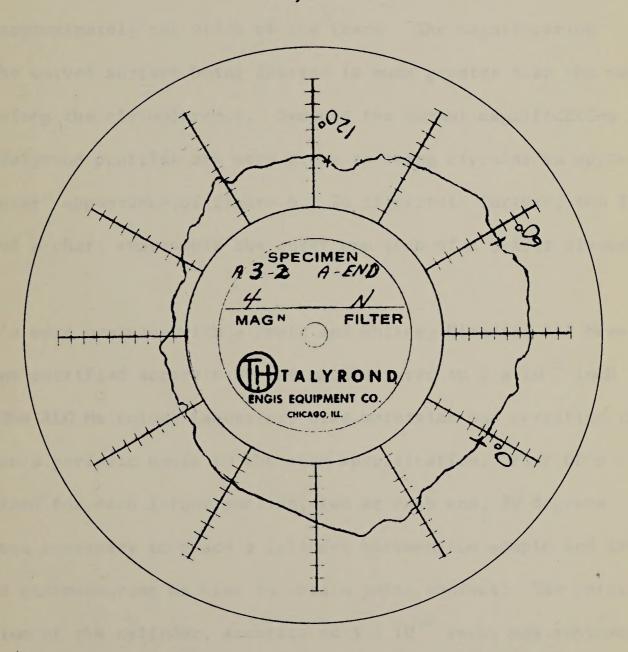


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		nch	
Sample number	0 °	60°	120°
3-2-A	0.03048	0.03051	0.03054

Talyrond



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Figure 6.-Cross section profile of a trilobular capillary bore.

Figure 7.-Cross section profile of an irregular capillary bore.

profiles. It is not necessary that the work be accurately centered in order to show true deviations from roundness.

Each Talyrond chart division represents 50 x 10⁻⁶ inch, reproducible to approximately the width of the trace. The magnification normal to the curved surface being charted is much greater than the magnification along the circumference. Because the normal magnification is 2,000, the Talyrond profiles are very close to being circular in spite of the "trilobular" appearance of figure 6. To illustrate further, the 1-inch scale of a chart represents the outer one inch of a 5-foot diameter circle.

The OD's were measured with a Pratt and Whitney Standard End Measuring Machine certified accurate by the manufacturer to 5×10^{-6} inch per inch. The ALO Metrology Laboratory also maintains and certifies the instrument on a periodic basis to the same specification. Four OD's were determined for each 1-foot section, two at each end, 90 degrees apart. It was necessary to place a cylinder between the sample and the anvil of the end-measuring machine to obtain point contact. The certified dimension of the cylinder, accurate to 5×10^{-6} inch, was subtracted from each reading to obtain the OD values listed in table 2. The apparent accuracy of the OD's is 10×10^{-6} inch. The average OD computed from all measurements is 0.122020 inch.

exection. It is not necessary that the work he occurately rentered in order to show true designations from roundness.

Lack laterend than director represents the later inch improducints to any oppositions of the state the much greater than the maynormal to any curved sorters point charled in much greater than the maynifronting atom, the director companies are made to state the state of 2,000, the laterent follows are very close to state circular to epitte of the "Epitember" appointment of figure to distinct the thinker, the 1lock coals at a chart sepressors the burst one into of a bisoch themselve offere.

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TABLE 2. - External diameter measurements

Sample number		outside diam	eter, inch		Average
1	0.12214	0.12214	0.12203	0.12203	0.122085
2	. 12210	.12202	. 12212	. 12208	.122080
3	.12209	. 12207	.12212	. 12211	.122098
4	.12210	.12206	. 12215	.12207	.122095
5	.12197	. 12205	.12206	.12206	. 122035
6	.12211	. 12197	. 12214	.12199	. 122052
7	.12192	.12180	.12205	.12195	.121930
8	.12202	. 12199	. 12212	.12200	. 122032
9	.12202	. 12200	.12203	. 12199	. 122010
10	. 12200	. 12195	. 12204	.12201	. 122000
11	.12211	. 12196	.12203	. 12196	.122015
12	. 12204	. 12205	. 12210	. 12205	.122060
13	. 12206	.12197	.12203	. 12201	. 122018
14	. 12204	. 12195	.12213	. 12209	.122052
15	.12202	.12199	. 12195	. 12194	.121975
16	. 12189	. 12199	. 12213	.12202	. 122008
17	. 12180	.12186	.12204	. 12195	. 121912
18	. 12200	.12187	. 12212	. 12191	. 121975
19	. 12195	. 12201	.12193	. 12190	. 121948

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The 1-foot sections were weighed on a 2-kilogram capacity analytical balance to 0.1 milligram. The National Bureau of Standards method of transposition $(8)^{4/}$ was used with certified stainless steel standard

4/Underlined numbers in parentheses refer to items in the list of references at the end of this report.

weights. Results of the weighings are given in table 3. The average apparent mass versus brass is 1.420717 grams per inch with an average deviation of ± 0.00041 .

The lengths of the 1-foot sections are given in table 3. With a section placed in the fixture (figure 1), a "best size" measuring wire was inserted in each end of the tube to establish the true centerline. The SIP optical system was used to measure the chord length from the center of the bore at one end to the center of the bore at the other end. The arc length (length of bore) was computed from:

$$L = \frac{\pi (10.00000 + a) \theta}{180}, \qquad (2)$$

where "a" is one-half the average OD of the bore, and θ is the angle of the sector in degrees.

Longitudinal internal surface finish measurements were taken with a Taylor, Taylor, and Hobson "Talysurf" Surface Finish Measuring Machine, which charted both surface finish and waviness relative to a 1-microinch optically-flat reference master. The readout capability of this instrument is 5×10^{-7} inch with interpolation to 1×10^{-7} inch

The 1-foot sections were weighted on a 2-billogram capacity analysis bordeness to be a section of the decision bordeness of transportation to 1 and 1

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The largest of the 1-foot sections are given in table 3. With a section placed in the fixture (liques 1), a "heat size" measuring three was inserted in each end of the total to entablish the contextine. The SIP optical gratem due nawd to measure the chord length trum the context of the bore at one end to the center of the bore it the other end. The are length (length of bore) was computed from:

(2) (E+00000.07) by a y

where "a" to one-half the average 00 of the bore, and 8 to the saule of the sector in dangeres.

Longitudinal internet surface timish housest very tures with the cutting the south of the surface of the surface of the surface of the surface to a selective of the surface of the surface to a selective to a selectiv

TABLE 3. - Length and mass measurements

	Length	Length	Apparent	
Sample	(chord),	(arc),	mass vs	True mass,
number	in	<u>in</u>	brass, g	g
1001203	11.22542	11.90849	16.93405	16.93417
2	. 18213	.85637	16.85823	16.85835
3	.28229	.97709	17.02168	17.02180
4	.21809	.89966	16.91229	16.91241
5	.24830	.93607	16.95357	16.95369
6	. 24382	.93067	16.94858	16.94870
7	.21662	.89790	16.89985	16.89997
8	.23920	.92510	16.94461	16.94473
9	.19920	.87692	16.87065	16.87077
10	.22077	. 90289	16.91059	16.91071
11	.21817	.89976	16.90626	16.90638
12	. 19385	.87047	16.86611	16.86623
13	.22249	.90496	16.90857	16.90869
14	.20648	.88568	16.88125	16.88137
15	.23230	.91679	16.91755	16.91767
16	.21202	.89235	16.89588	16.89600
17	.19275	.86916	16.86279	16.86291
18	.21400	.89474	16.88976	16.88988
19	.17942	.85312	16.83715	16.83727

TABLE 3. - Lingth and case consumments

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along 1/4-inch lengths of exposed surface. The accuracy of surface finish measurements is considered one microinch, including procedural and calibration errors. Arithmetically averaged internal surface roughnesses were five, eight, six, eight, eight, and six microinches. Any minor projection or burr in the capillary wall which is less than 10 microinches will not measurably affect the laminar flow profile.

CONFIRMATION OF MEAN RADIUS THROUGH TALYROND CHARTS

The Talyrond measures out-of-roundness, not actual diameter. The determination of an average "cross sectional" radius from a Talyrond chart depends on relating the chart scale to the diameters measured directly with the SIP. This was accomplished using the SIP reference 0° mark at each end of the 4-inch sections. When the sections were run on the Talyrond, each chart was marked at 0°, 60°, and 120°. In figure 5, "bottom of scale" is the inner circle from which the chart scales radiate at 30-degree intervals. Each division of a chart scale is 0.1 inch, and represents 50×10^{-6} inch actual travel by the Talyrond stylus. The chart diameter at "bottom of scale" is two inches. The "equivalent distance at bottom of scale" was determined at each known diameter (0°, 60°, 120°) by measuring the distance across the chart trace, subtracting the chart diameter at "bottom of scale" (two inches), and dividing by 0.1 inch per division to get the number of chart divisions. The accuracy of measuring the distance across the chart was 0.01 inch corresponding to 0.000005 inch in determining "equivalent distance at bottom of scale" and is well within the accuracy of the SIP.

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chart divisions were converted to actual inches by multiplying by 50 x 10^{-6} inch per division. This number was subtracted from the corresponding measured SIP diameter to give "equivalent diameter at bottom of scale." The "equivalent radius at bottom of scale" for each Talyrond chart is the average of the three "equivalent diameters," divided by two.

The area enclosed by the line traced on the chart was measured with a planimeter calibrated in square inches. The radius of a true circle having the same area was computed; the chart radius at bottom of scale (one inch) was subtracted from the computed radius, and the remainder was converted to chart divisions (0.1 inch = one division). The chart division value was converted to actual inches (times 50×10^{-6}) and added to the "equivalent radius at bottom of scale." This procedure gave an average radius for each of the 114 cross sections as shown in table 4. The average of all cross sections is 0.015201 inch, which compares very favorably with the 0.015199 inch SIP average and provides confirmation of the SIP diameters. A sample calculation follows for Talyrond chart sample 1-1-B (figure 5).

Equivalent distance at bottom of scale:

 $0^{\circ}:3-25/64$ in - 2 in = 1.391 in = 13.91 div = 0.000695 in; $60^{\circ}:3-5/16$ in - 2 in = 1.312 in = 13.12 div = 0.000656 in;

120°:3-5/16 in - 2 in = 1.312 in = 13.12 div = 0.000656 in.

Equivalent diameter at bottom of scale:

 $0^{\circ}:0.03057(SIP) - 0.000695 = 0.029875 in;$

 $60^{\circ}:0.03049(SIP) - 0.000656 = 0.029834 in;$

chart divisions were concerted to signal introduct by multiplying by 10 m

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The send emissed by the true trees on the chair was measured with a planteness of all true circles and the rame send on the chair radius of a true circle (one than the their radius of notion of scale (one then) are subtracted from the evapored radius, and the remainder was converted to their directions (0.1 lach a use officials). The chart division of actual taking (from 30 a 10 b) and division value are converted to actual taking (from 30 a 10 b) and added to the "equivalent radius at horizon of scale." This procedure gave as secage radius for each of the like cross southers as about to taking a subject to the construction of the site of the like the state of the like colored to the like and the contract of the contract of the like and the colored to the construction of the Sit discountry. A sample calculation roture for

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0°:3-25/64 10 - 2 10 * 1.397 10 - 13.97 019 = 0.000005 10: 60°:3-5/16 10 - 2 10 - 1.312 10 * 13.72 219 - 2.000650 10: 20°:3-5/16 10 - 2 10 - 3.517 10 - 13.12 219 = 0.000650 10:

0*:0.03037(8%2) - 0.000093 - 0.029375 Ln;

TABLE 4. - Radii computed by integrating the Talyrond charts

Sample number	Talyrond radius, inch	Last 3 digits of average SIP	Sample number	Talyrond radius,	Last 3 digits of average SIP
1-1-A 1-1-B 2-1-A 2-1-B 3-1-A 3-1-B	0.015234 .015237 .015193 .015200 .015195 .015218	232 245 197 205 200 223 217	1-2-A 1-2-B 2-2-A 2-2-B 3-2-A 3-2-B Ave	0.015220 .015194 .015244 .015242 .015274 .015272 rage .015241	220 200 240 252 255 <u>253</u> 237
1-3-A 1-3-B 2-3-A 2-3-B 3-3-A 3-3-B	0.015180 .015259 .015246 .015215 .015172 .015182 .015209	187 260 240 225 187 182 214	1-4-A 1-4-B 2-4-A 2-4-B 3-4-A 3-4-B	0.015140 .015206 .015200 .015196 .015175 .015204 .015187	150 187 203 193 172 215 187
1-5-A 1-5-B 2-5-A 2-5-B 3-5-A 3-5-B	0.015156 .015202 .015216 .015187 .015214 .015202 .015197	165 195 208 192 217 193	1-6-A 1-6-B 2-6-A 2-6-B 3-6-A 3-6-B	0.015200 .015176 .015210 .015224 .015222 .015186 .015203	200 162 212 218 207 178 196
1-7-A 1-7-B 2-7-A 2-7-B 3-7-A 3-7-B	0.015193 .015196 .015200 .015203 .015214 .015217 .015204	167 182 195 193 208 208 192	1-8-A 1-8-B 2-8-A 2-8-B 3-8-A 3-8-B	0.015214 .015195 .015202 .015239 .015238 .015235	203 197 188 230 232 220 212
1-9-A 1-9-B 2-9-A 2-9-B 3-9-A 3-9-B	0.015226 .015203 .015230 .015221 .015187 .015226 .015215	215 195 222 210 193 215 208	1-10-A 1-10-B 2-10-A 2-10-B 3-10-A 3-10-B	0.015212 .015208 .015194 .015207 .015207 .015210 .015206	215 212 183 215 197 208 205

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TABLE 4. - Radii computed by integrating the Talyrond charts
Continued

Sample number	Talyrond radius, inch	Last 3 digits of average SIP	Sample number	Talyrond radius, inch	Last 3 digits of average SIP
1-11-A 1-11-B 2-11-A 2-11-B 3-11-A 3-11-B	0.015201 .015202 .015183 .015200 .015218 .015195*	190 195 182 193 198 202 193	1-12-A 1-12-B 2-12-A 2-12-B 3-12-A 3-12-B	0.015171 .015199 .015177 .015112 .015181 .015176 .015170	178 182 172 113 177 167
1-13-A 1-13-B 2-13-A 2-13-B 3-13-A 3-13-B	0.015168 .015176 .015174 .015221 .015195 .015215 .015192	162 183 187 208 192 207 190	1-14-A 1-14-B 2-14-A 2-14-B 3-14-A 3-14-B	0.015199 .015201 .015239 .015235 .015213 .015239	197 207 220 223 218 222 214
1-15-A 1-15-B 2-15-A 2-15-B 3-15-A 3-15-B	0.015233 .015223 .015229 .015218 .015210 .015232	232 220 215 202 213 220 217	1-16-A 1-16-B 2-16-A 2-16-B 3-16-A 3-16-B	0.015222 .015214 .015223 .015225 .015190 .015185 .015210	217 212 230 220 210 <u>195</u> 214
1-17-A '1-17-B 2-17-A 2-17-B 3-17-A 3-17-B	0.015205 .015216 .015226 .015199 .015176 .015173	202 208 225 200 175 170	1-18-A 1-18-B 2-18-A 2-18-B 3-18-A 3-18-B	0.015175 .015190 .015173 .015172 .015154 .015171	173 188 180 160 152 160 169
1-19-A 1-19-B 2-19-A 2-19-B 3-19-A 3-19-B	0.015189 .015144 .015124 .015143 .015154 .015167	192 138 148 152 155 <u>158</u> 157			

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$$120^{\circ}:0.03041(SIP) - 0.000656 = 0.029744 in;$$

$$Average = 0.029818 in.$$

Equivalent radius at bottom of scale = 0.014909 in.

Area measured by planimeter = 8.62 in^2 .

Radius of circle with same area = $(8.62/\pi)^{1/2}$ = 1.656 in;

1.656 - 1.000 = 0.656 in = 6.56 chart div;

 $(6.56 \text{ chart div})(50 \times 10^{-6} \text{ in/div}) = 0.000328.$

Average radius of cross section (1-1-B) = 0.014909 + 0.000328;

= 0.015237 in.

Average radius of three (1-1-B) SIP measurements = 0.015245.

CORRECTION FOR NON-UNIFORMITY OF CAPILLARY BORE

Capillary tube viscosimeters can be considered as an infinite number of uniform, right circular cylinders arranged in series. This concept leads to correcting the hypothetical mean radius, $R_{\rm m}$, in equation (1) to approximate more closely the real case and has been discussed by Barr ($\underline{1}$, p. 61), Flynn ($\underline{3}$, p. 25), Giddings ($\underline{4}$, p. D-8), Lemaire ($\underline{7}$, p. 21), and Swindells and coworkers ($\underline{10}$, p. 17). This report designates the correction as

$$\delta = \frac{\sum_{i=1}^{n} \left(\frac{R_{m}}{R_{i}}\right)^{4}}{n} = \frac{\sum_{i=1}^{n} \left(\frac{L_{i}}{R_{i}^{4}}\right)}{\left(\frac{L_{T}}{R_{m}^{4}}\right)}, \qquad (3)$$

where L_i is a constant or $L_i = L_1 = L_2 = L_3 = \cdots = L_n$. Ideally, n is infinite. In the practical case, however, n can be some finite number

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Complete of positions, right election or considered on an infinite monder of position, right election cylinders arranged in scribe. This concept lends to correcting the hypothetical news redices, R₀, in equal tion (1) to approximate more closely the real rise and has been distracted by Barr (1, p. 61), Figur (2, p. 25), Caldings (6, p. 0-5), Lendtry (1, p. 21), and Sentidally and concepts (10, p. 17). This request destinates the correction on

where to is a nonstrant or i, - i, - i, - i, - . - - i, Ideally, c is intinized in the some Civite number.

of samples whereby the evaluation of δ and its insertion into equation (1) may or may not be of significance in computing viscosity, depending on the magnitude of the non-uniformity of the capillary bore. Utilizing the 114 individual SIP radii leads to a value for δ of 1.000030; δ equals 1.000035 using the individual Talyrond radii. In either case, the error in computing viscosity is less than 0.01 micropoise when the viscosity is 200 micropoises.

In computing δ from the average radii tabulated in table 1, the following procedure was used. For sample 1-1-A, the front end of the first 4-inch sample, the average radius of 0.015232 inch was assumed to apply to the first two inches; the average radius for the back end (1-1-B) of this same 4-inch sample, 0.015245 inch, was assumed to apply to the other two inches of this sample. In other words, each averaged radius in table 1 represents a uniform bore of 2-inch length, L.

Figure 8 shows the deviation of the 19-foot capillary bore from the

Figure 8.-Deviation of the capillary bore from the average radius.

average SIP radius, $R_{\rm m}$, in millionths of an inch. The plotted values are the 1-foot averages shown in the last column of table 1; the maximum deviation is about 40 millionths of an inch.

Figure 9 is a frequency distribution graph of the 342 SIP diameter

Figure 9.-Distribution of SIP diameter measurements.

For equiple 1-1-4, the

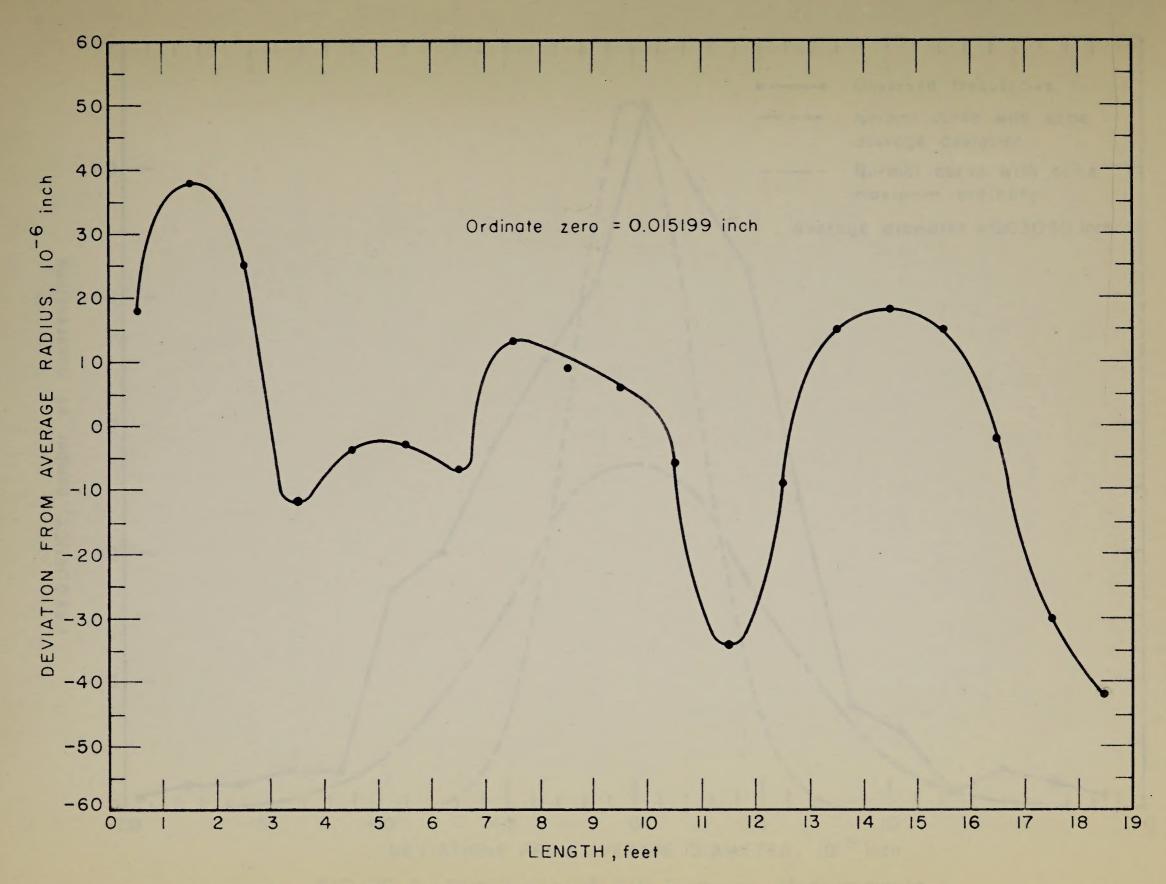


FIGURE 8.-Deviation of the Capillary Bore from the Average Radius

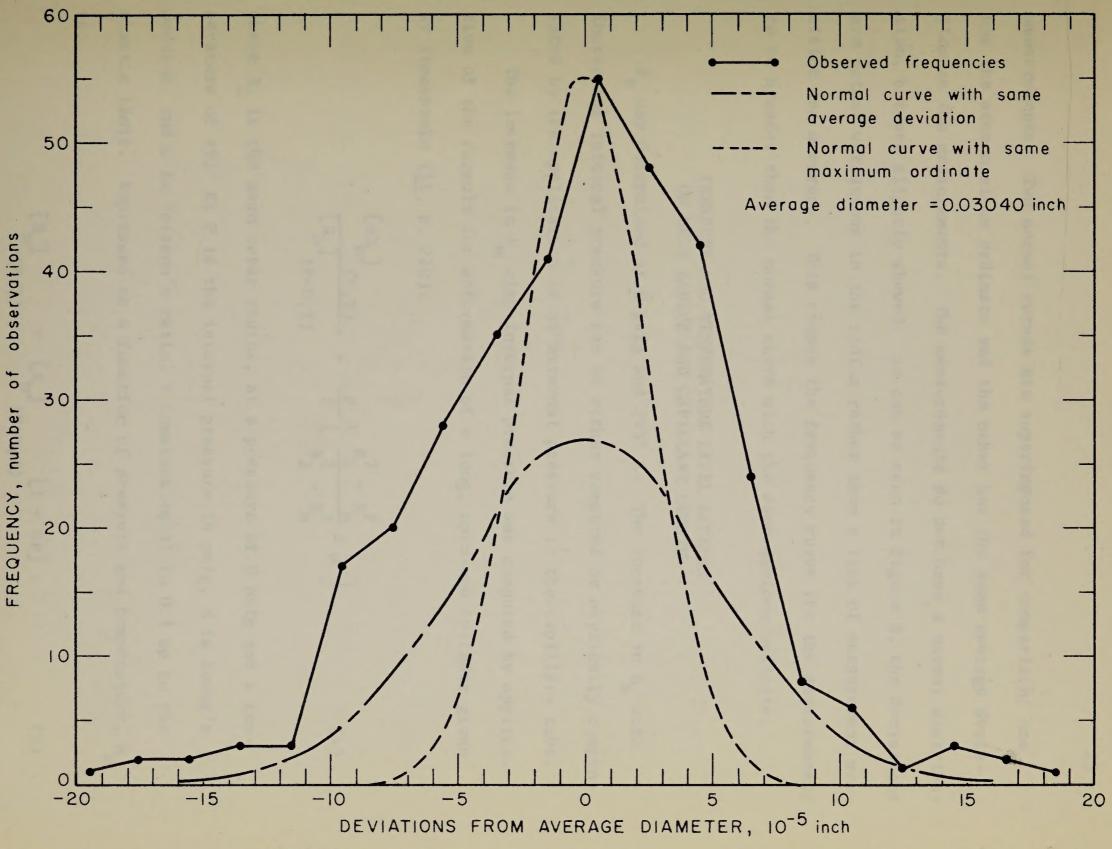
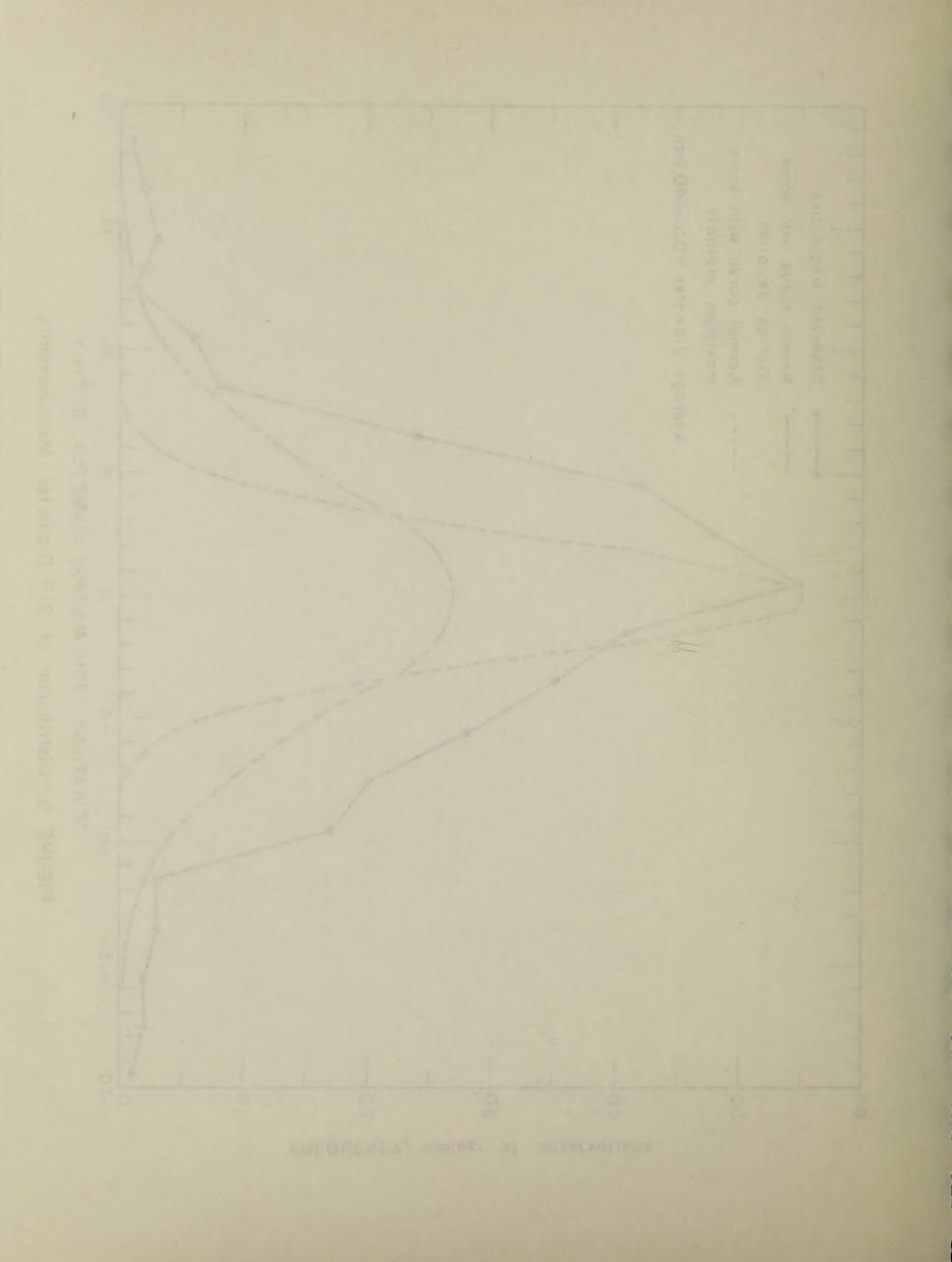


FIGURE 9.-Distribution of SIP Diameter Measurements



measurements. Two normal curves are superimposed for comparison; one has the same maximum ordinate and the other has the same average deviation as the measurements. The measurements do not have a normal distribution, but are slightly skewed. As can be seen in figure 8, the deviations are actual variations in the radius rather than a lack of measurement precision and accuracy. This causes the frequency curve for the measurements to be broader than the normal curve with the same maximum ordinate.

PRESSURE AND TEMPERATURE LEVEL EFFECTS ON MEAN RADIUS AND CAPILLARY LENGTH

 $R_{\rm m}$ was determined at 0 psig and 293° K. The increase in $R_{\rm m}$ with increasing internal pressure can be either computed or physically compensated by the application of an external pressure to the capillary tube.

The increase in $R_{\rm m}$ with internal pressure was computed by application of the formula for deformation of a long, open-end cylinder given by Timoshenko (11, p. 210):

$$\frac{\left[\triangle R_{m}\right]_{(P,T)}}{\left[R_{m}\right]_{(P=0,T)}} = \frac{P}{E} \left[\frac{R_{2}^{2} + R_{m}^{2}}{R_{2}^{2} - R_{m}^{2}} + \mu \right], \tag{4}$$

where R_2 is the mean outer radius, at a pressure of 0 psig and a temperature of 293° K; P is the internal pressure in psig; E is Young's modulus; and μ is Poisson's ratio, a constant equal to 0.3 up to the elastic limit. Expressed as a function of pressure and temperature, R_m is:

$$[R_{m}]_{(P,T)} = [R_{m}]_{(P=0,T)} [1 + \beta P], \qquad (5)$$

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measurements. Two normal curves are superingued for comparison; one has the same maximum ordinate and one order has the team overage daviation at the measurements. The measurements do not have a measure distribution, but are singuly shored. As one he seem in figure 8, the deviations are accord variations in the reduct mather than a lack of measurement pre-

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terreacing internal pressure one to extror exercise to the content tonestsured by the application of on verteral pressure to the expiliary time.

The increase in P with internal pressure was commond up supliceclos of the formula for delignation of a long, own-and cylinder piven

where he the mean more reduced in present of pate and a tenpurature of 201' K: F is the important presents for pate. E is round's codulus; and a is Folsoon's ratio, a constant to 0.0 up to the elastic limit, depressed as a function of presents and consequent. A

where β , the pressure expansion coefficient, is:

$$\beta = \frac{1}{E} \left[\frac{R_2^2 + R_m^2}{R_2^2 - R_m^2} + \mu \right]. \tag{6}$$

Also,

$$\begin{bmatrix} R_{\rm m} \end{bmatrix}_{\rm (P=0,T)} = \begin{bmatrix} R_{\rm m} \end{bmatrix}_{\rm (P=0,293^{\circ}K)} \begin{bmatrix} 1 + \alpha \triangle T \end{bmatrix}, \qquad (7)$$

where α is the thermal expansion coefficient.

The thermal expansion coefficient, α , of 347 stainless steel is given by Corruccini and Gniewek ($\underline{2}$, p. 12) and Schwartzberg and coworkers ($\underline{9}$, p. B.7.t); Young's modulus as a function of temperature is given by the latter ($\underline{9}$, p. B.7.ij). From these references it was determined that:

$$\alpha = f(T) = C_1 + C_2 T + C_3 T^2$$
 (8)

and

$$\beta = f(T) = (C_4 + C_5 \triangle T), \qquad (9)$$

where C_1 , C_2 , C_3 , C_4 , and C_5 are constants, T is degrees Kelvin, and $\triangle T = T - 293$; the values of the constants are: $C_1 = 1.07418 \times 10^{-5}$, $C_2 = 2.97565 \times 10^{-8}$, $C_3 = -4.230 \times 10^{-11}$, $C_4 = 5.502 \times 10^{-8}$, and $C_5 = 1.97 \times 10^{-11}$.

Therefore,

$$[R_{\rm m}]_{(P,T)} = [R_{\rm m}]_{(P=0,293^{\circ}K)} [1 + \alpha \triangle T][1 + \beta P] .$$
 (10)

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The capillary length as a function of temperature is:

$$L_T = f(T) = [L_T]_{(293°K)} [1 + (c_1 + c_2T + c_3T^2) \triangle T],$$
 (11)

where C_1 , C_2 , C_3 , T, and $\triangle T$ are the same as previously defined.

Incorporating the temperature and pressure corrections into equation (1) gives

$$\eta = \left[\frac{\pi \triangle P_{e} \left[R_{m}^{4} \right]}{8 \ Q_{m} \ L_{(293^{\circ}K)}} \right] \\
\left[1 + (c_{1} + c_{2}T + c_{3}T^{2}) \triangle T \right]^{3} \tag{12}$$

as δ was shown to be negligible.

Over the pressure range 28 to 1,000 psia, the calculated change in $R_{\rm m}$ is less than 10 microinches. Higher internal pressures will significantly affect viscosity calculations. Both $L_{\rm T}$ and $R_{\rm m}$ change with temperature by approximately 0.001 percent per degree Kelvin. Because the viscosimeter will be operated over wide ranges of temperature and pressure, both corrections are retained in the final working equation for viscosity, equation (12).

AVERAGE RADIUS AND DENSITY EVALUATION BY DIFFERENT METHODS

Superior Tube Company suggested a value of 0.2833 lb/in for the density of the 347 stainless steel tubing, based on mole percent weight-

The captillary longer on a cumction of temperature is:

$$(11) - [11]^{2} = (1)^{2} - [1] + (1) + (2)^{2} + (2)^$$

Where Co. Co. Co. Co. T. and AT are the asses or proviously defined.

Incorporating the isoperature and pressure corrections into equation (1) gives

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Over the pressure range 28 to 1,000 peta, the coloulated change in R is less than 10 microfuches. Higher internal pressures with significantly affect viscosity calculations. Both L and R change with temperature by approximately 0.001 percent per degree Kelvin. Secause the viscosimeters will be operated over wide ranges of temperature and pressure, both corrections are retained in the final working equation for viscosity, equation 112).

AVERAGE REDTHS AND DENSITY EVALUATION.

Superior Tube Company suggested a value of 0,2813 lb/in for the

ing from composition analysis. Specific gravity determinations, using distilled water, by the Pantex facility gave 0.2862 lb/in 3 for a randomly-selected, 1-foot section. An average density of 0.2856 lb/in 3 was computed from the average SIP $R_{\rm m}$ and the volumetric method (page 7). The latter density value was taken to be the most accurate.

Values for $R_{\rm m}$ were computed by the volumetric method using the Superior Tube Company and Pantex densities. Using a gas expansion technique 5 which is independent of density, $R_{\rm m}$ values were determined

for the 32- and 208-foot long capillary tubes as well as an 85-foot long section. These data are summarized in table 5.

ENTRANCE, KINETIC ENERGY, GAS SLIPPAGE, AND GAS COMPRESSIBILITY EFFECTS

The entrance and kinetic energy effects are discussed together; the effects of gas slippage and gas compressibility are examined similarly. These are applied to the 32-foot (971.704 cm) long capillary in the form of a coil 20 inches in diameter using nitrogen at 300° K and pressure levels of 28 and 1,000 psia. It is assumed, a priori, that entrance, kinetic energy, and gas slippage effects for straight tube capillaries apply to the coil.

Further information regarding the gas expansion technique developed at the Helium Research Center is available upon request from the Research Director, Helium Research Center, Bureau of Mines, Amarillo, Texas.

Values for N, were computed by the volumetric method using the Superior labe Company and Penter denotices. Heing a gus expection cocharque which is independent of density; N, values were determined

Further information regarding the gas expansion technique developed at the Helium Rescuren Concer is available open request from the Cosmich Director, Helium Rescutch Conter, Bureau of Miney, Assellie, Dess.

For the 32- and 208-font long capillary times as well as an 83-foot long sention. There date as a surrival to table 5

ENGLANCE, KINEFIC EXHIBITY CAS SALEDAGE.

The entrence of gas alippage and gas compressibility are casmined simiine effects of gas alippage and gas compressibility are casmined similarly. There are applied to the 32-feet (0)1.70% cm) long capillary in
the form of a call 20 inches in discuster using nitrogen at 300 % and
pressure levely of 28 and 1,000 yeld. It is naturally a priori, that
capillaries apply to the cell.

TABLE 5. -Average radius and density evaluation by different methods

Density			recepting a circle	
<u>lb/in³</u>	Source	Method	$\frac{R_{\rm m}, \text{ in } \frac{1}{}}{}$	$\frac{L_{T}, ft}{}$
0.2833	Superior Tube Company	Volumetric	0.014281	19
.2862	Pantex Plant	on one two and pan $q \circ o$ on one one can one	.015492	19
Oled Child Child Child Child Child	Helium Research	Gas expansion	.015334	32
	Center	The root	of Tinkhon and	111
		one can can can day Q O one can bee one one	。015399	85
	one can can can can can $d \odot$ can can con can can	сме они сис они О В они сис сис сис сис	.015130	208
2/ .2856	and any two two can can d Q (see two two two two	SIP	.015199	19

^{1/} Average, not including SIP, equals 0.015127 in; average, gas expansion, equals 0.015287 in; average, all, equals 0.015305 in.

^{2/} Computed from SIP and volumetric measurements.

Entrance and Kinetic Energy Effects

Couette suggested correcting Poiseuille's equation for external resistance for the case of flow streamlines entering a thick-walled capillary from a larger conduit, past a square-cut end; further, Brillouin showed that this could be expressed as a hypothetical addition to the length, $L_{\rm T}$. The expression for this extra length is nR where n is a constant between 0.8 and 0.9. The work of Couette and Brillouin is detailed by Barr ($\underline{1}$, p. 20). Using a value of 0.9 for n and 0.0152017 inch (0.0386 cm) for R yields at 300° K and 1,000 psia:

$$L_T + nR_m = 971.742 \text{ cm}$$
 (13)

A calculated viscosity of 200.06 micropoises changes to 200.05 by correcting for the entrance effect. This change is negligible.

The kinetic energy correction, as shown by Barr ($\underline{1}$, p. 15) and Swindells and coworkers ($\underline{10}$, p. 2), results from acceleration of the streamlines after entering the constricted capillary and is included in the measured pressure drop, $\triangle P_{me}$. If the assumptions are made that steady-state laminar volumetric flow exists at the entrance and that the same kinetic energy is retained throughout the capillary (that is, Q_m is constant), then:

$$\triangle P_{\text{me}} = \triangle P_{\text{e}} + \triangle P_{\text{Ke}} , \qquad (14)$$

where $\triangle P_{e}$ is the pressure drop used to overcome viscous resistance and $\triangle P_{Ke}$ is the pressure drop due to kinetic energy. By way of Barr (1, p. 17), it can be shown that:

Intended and Storette Emergy Effects

Country that the twee of flow extremitions entering a thirt-walled capitalists from a larger conduct, past of equate out-top, a thirt-walled capitalists from a larger conduct, past of equate out-top forther, and the appetuance as a top exhabit at admitted to the larger, and the appetuant of the contract of the contra

my far. HV = An - A

A calculated windowstry of 100.00 micropoless changes to 200.05 to correcting for the entrance elices. This change is delighbles.
The Kinesto energy correction, or chows by last (1, p. 15) and

Cuindella and amerikasa (10, p. 1), results from accontration of the eigenstance electricity and in tryinded in the measures greaters drop if the committee of the contrate the area of the contrate the

where AT, is the present drop and to handle energy. We may of fair II.

$$\Delta P_{e} = \Delta P_{me} - \frac{m\rho Q_{m}^{2}}{\pi^{2} R_{m}^{4}}, \qquad (15)$$

where m is a characteristic physical constant nearly equal to unity and ρ is the density of the flowing fluid. The kinetic energy correction for short capillaries at high volumetric flow rates is significant.

At 1,000 psia and 300° K, the density of nitrogen was interpolated to be 0.07428 g/cm 3 from Flynn ($\underline{3}$, p. 123). Average experimental values for Q_m and ΔP_{me} were 0.02222 cm 3 /sec and 0.0678 psi, respectively. For these conditions R_m equals 0.0152017 inch or 0.038612 cm. Substituting into equation (15) gives, for the last term, a value of 1.67 dynes/cm 2 or about 2.4 x 10 $^{-5}$ psi which is negligible compared to ΔP_{me} . A viscosity of 200 micropoises would change by 0.05 micropoise by making the correction.

Gas Slippage and Gas Compressibility Effects

By kinetic theory considerations it can be deduced that, in the immediate vicinity of the capillary wall, a layer of gas thinner than the mean free path, λ , of the molecules has a finite velocity (slip) in the direction of flow. It can be shown by way of Klinkenberg ($\underline{6}$, p. 4) that the modified Poiseuille equation, corrected for gas slippage, is

$$\eta = \left[\frac{\pi R_{\rm m}^{4} \triangle P_{\rm e}}{8L_{\rm T}Q_{\rm m}} \left(1 + \frac{4c\lambda}{R_{\rm m}} \right) \right], \qquad (16)$$

where m is a characteristic physical constant meanly equal to unity and p is the density of the flowing-field. The kinetic anargy correction for short capillaries at high patometric flow cates is arguillable.

At 1,000 pais and 100° E, the density of nitrogen was interpolated to be 0.07678 g/or from flynn (1, p. 123). Average experimental values for these conditions R equals 0.07570; inch or 0.075812 cm. Substituted that equals 0.07570; inch or 0.075612 cm. Substituted that equals 0.07570; inch or 0.075612 cm. Substituted for security of the last torm, a value of 1.07

steadstry of 200 migropulses would change by 0.05 microbotes by maring

Cas Sirgues and Gas Compressibility Effects

by binesic theory commissestions it can be deduced that, in the immediate vicinity of the repliety well, a layer of gas thinner than the mean free path, i, of the molecules has a finite velocity (slip) (a the direction of flow. It can be shown by may of filmienberg (g. p. 4) that the modified retarnille equation, corrected for gas slippage. In

where c is a numerical constant nearly equal to unity. According to Guevara and Wageman (5, p. 19), this constant has been calculated to be 1.147. A reasonable estimate of the effect of slippage, the term in parentheses, needs to be made at the lowest pressure level, 28 psia, because slippage is more significant at low pressures (and temperatures).

From Flynn ($\underline{3}$, pp. 123, 127), extrapolated density and viscosity values for nitrogen at 28 psia and 298° K were 2.33 x 10^{-3} g/cm³ and 178 micropoises, respectively. The mean free path was computed to be 488 x 10^{-8} cm from simple kinetic theory considerations; λ equals $3\eta/\rho c$, where \overline{c} is the average molecular speed. The value of $4\lambda/R_m$ at 298° K, assumed to apply at 300° K, was evaluated to be 506 x 10^{-6} cm. The value of the slippage term is 1.000506, corresponding to a viscosity correction of 0.1 micropoise.

The differential equation for isothermal steady-state laminar flow of compressible fluids, neglecting slippage, is:

$$Q_{m} \int_{0}^{L_{T}} dL = -\frac{\pi R_{m}^{4}}{8\eta} \int_{P_{1}}^{P_{2}} \left[\left(\frac{Z_{m}}{Z}\right) \left(\frac{P}{P_{m}}\right) \right] dP , \qquad (17)$$

where Z_m is the compressibility factor for the fluid at the mean system pressure, $P_m = (P_1 + P_2)/2$, and Q_m is the volumetric flow rate at P_m .

For nitrogen, the change in Z from the entrance of the capillary (P_1) to the exit (P_2) is approximately 1 x 10^{-5} at 300° K. The pressure drop across the 32-foot long capillary, at 28 and 1,000 psia, was less

Consequent and Campanan (5) or 17), tyle concerns has been conculing to be grown and the contributed to be a segmental as a segmental of the contributed to be selected as the contributed to be selected as the lowest presents as the contributed to the contributed as the contribut

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where I is the compressibility factor for the flow and in the man artists of the man artists pressure, F = (F + F 2)/2, and Q is the volumerary flow cuts at F ...

For nitrogen, the charges in 2 from the entrance of the captillary ...

(F) to the rait (F) is approximately 1 a 10 at 200 E. The pressure dry across the 12-toot rong capillary, at 10 at and 1,000 pater.

than one psi. The ratio $Z_{\rm m}/Z$, then, is so close to unity that it can be removed from the integral and the compressible gas treated as incompressible as long as this condition obtains.

SUMMARY

Special methods have been developed for measuring physical dimensions of small diameter tubing, and for evaluating the parameters associated with Poiseuille-type viscometry which are inherently dependent on those dimensions. As far as the authors are aware, this study represents the first time that a long section of stainless steel capillary tubing has been comprehensively examined by metrological methods for use in an absolute gas viscosimeter. As the capillary mean radius is considered accurate to 10 millionths of an inch, viscosities can be determined to one micropoise or better. An accurate appraisal of the non-uniformity of the capillary bore, or variations of radius along the length, is made. Although the individual radii are slightly skewed from a normal distribution, the deviations are actual variations in radii rather than a lack of measurement precision. The internal surface finish of the tubing will not measurably affect the viscosity determinations.

The effects of pressure and temperature on the mean radius and overall length are incorporated into a final working equation for viscosity. Corrections for bore non-uniformity, entrance effects, kinetic energy effects, and gas slippage, all implied to be negligible for the tubing used at low volumetric flow rates, can be included in the final working equation for greater accuracy. The capillary internal diameter measurethen one per . The route Z. is, then, is so close to the large and the per routed as interpreted at the contract of the large and the large an

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Since of shall discuss them developed by messaring physical characters of shall discuss the parameters at the parameters at the parameters at the parameters at the parameters of the parameters at the parameters. As the them and the standard are some, this standard represents the inter time that a long colling of the parameters are specified and the standard represents as the parameters as the parameters. As the capitliary were reduced for were to an accurate to 10 ministers of the capitliary were reduced as the capitliary there are the shortestand as one attroopers or better. An accurate appropriate of the conditionality of the capitliary before, or varieties of reduce along the length; is come. Although the today the length; is come. Although the today the length; is come. The deviational reduced the reduced from a normal discription measurement precision. The interest materials and the tideling will measurement precisions. The interest contractions are noticed to development of the tideling will measurement precisions. The interest contractions are noticed to development of the tideling will measurement precisions, the development of the tideling will and measurement precisions. The interest contractions are noticed to the tideling will contract the tideling will and the tideling will contract the contract the tideling will contract the contract of the tideling will contract the contract of the tideling will contract the contract of the tideling will be tideling will be tideling the tideling will be tideling to the tideling the tideling will be tideling the tideling the tideli

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ment and its accuracy, however, are the most significant physical parameters in capillary tube viscometry. Because of the very small pressure drops across the system, the gas is treated as an incompressible fluid.

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REFERENCES

- 1. Barr, Guy. A Monograph of Viscometry. Oxford University Press, London, 1931, 318 pp.
- Corruccini, Robert J., and John J. Gniewek. Thermal Expansion of Technical Solids at Low Temperatures. NBS Monograph 29, May 1961, 24 pp.
- 3. Flynn, George Patrick. The Viscosity of Nitrogen and Argon as a Function of Density and Temperature. Ph. D. thesis, Brown University, June 1962, 145 pp.
- 4. Giddings, John G. The Viscosity of Light Hydrocarbon Mixtures at High Pressures: The Methane-Propane System. Ph. D. thesis, Rice University, May 1963, p. D-8.
- 5. Guevara, F. A., and W. E. Wageman. Measurement of Helium and Hydrogen Viscosities to 2,340° K. Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 1965, 43 pp.
- 6. Klinkenberg, L. J. The Permeability of Porous Media to Liquids and Gases. Eleventh Mid-Year Meeting of the American Petroleum Institute, Tulsa, Oklahoma, May 22, 1941, 12 pp.
- 7. Lemaire, Normand Arthur. The Viscosity of Helium and Neon as a Function of Density and Temperature. Ph. D. thesis, Brown University, June 1962, 141 pp.
- 8. NBS. Design and Test of Standards of Mass. NBS Circ. No. 3, December 23, 1918, pp. 37-38. Paper in NBS Handbook 77, Precision Measurement and Calibration, v. 3, Optics, Metrology, and Radiation, February 1, 1961, pp. 655-656.

HEREBRURE SH

- Lordon, 1931, 318 no.
- 2. Commonth, Monett J., and John J. Ontevol. Marinel Deponsion of Technical Solites at Law Compensiones. Mas Monograph 25, Nov 1961, 24 pp.
- 3. Flying, George Calrick. The Viscolity of Mirroyen and Figure 2s. English of Denetion of Denetics and Temperature. The Detects, Grown Calver-eity; June 1962, 145 pp.
- A. diddings, john U The Viscosity of Light Minocorpor Mixtures at all the Meriano-Propano System. 20. United to the May 1965, p. D-8.
- S. Guernan, F. A., and U. E. Magan-r. Formurenest of Hotton and Hydro-gan Viscositives to 1, 340 K. Los Alamos School III Isboratory, Los Alamos School III Isboratory, Los Alamos School III Isboratory, Los
- Cases: Sleventh Mid-Year Meeting of the American Firston Instature, fulse, Ottobone May 27, 1991, 17 pp-
- Numerica of Density and Temperature. In B. thesis, Jean Univer-
- S. NSS. Design and Dest of Standards of Name. NOS Circ. No. 3, Dreem. ber 25, 1912, pp. 37-38. Pager in NSS Mandicol 77, Erncialon Near-inchest and Colimbration, v. 3, Optics, Markology, and Vadiation.

REFERENCES (Con.)

- 9. Schwartzberg, F. R., S. H. Osgood, R. D. Keys, and T. F. Kiefer.

 Cryogenic Materials Data Handbook. U. S. Department of Commerce,

 July 1965, pp. B.7.ij and B.7.t.
- 10. Swindells, J. F., J. R. Coe, Jr., and T. B. Godfrey. Absolute
 Viscosity of Water at 20° C. NBS J. Res., v. 48, No. 1, January
 1952, 31 pp.
- 11. Timoshenko, S. Strength of Materials, pt. 2, Advanced Theory and Problems. D. Van Nostrand Co., Inc., Princeton, N. J., 1956, 3rd ed., 572 pp.

L. noth & crustings

1

- 9. Schwarz Terz, F. R., J. H. Osgond, S. D. Voys, and T. E. Eldter, Cryogenic Mararials Data Masibook. U. S. Department of Concerce.
 - 10. Swindelle, J. F. J. W. Cob., Jr., and T. B. Gedjeep. Absolute
 Viscoulty of Nucer at 20° C. NES J. Res., v. 42, No. 1, Issuelt
 1952, 31 pp.
- 11. Timoshanko, S. Strongth of Managlain, pt. ., Advanced Livery and Problems. B. Van Magazeand Co., Inc., Princeton, E. U., 1935.







